Mask roughness: modeling and implications

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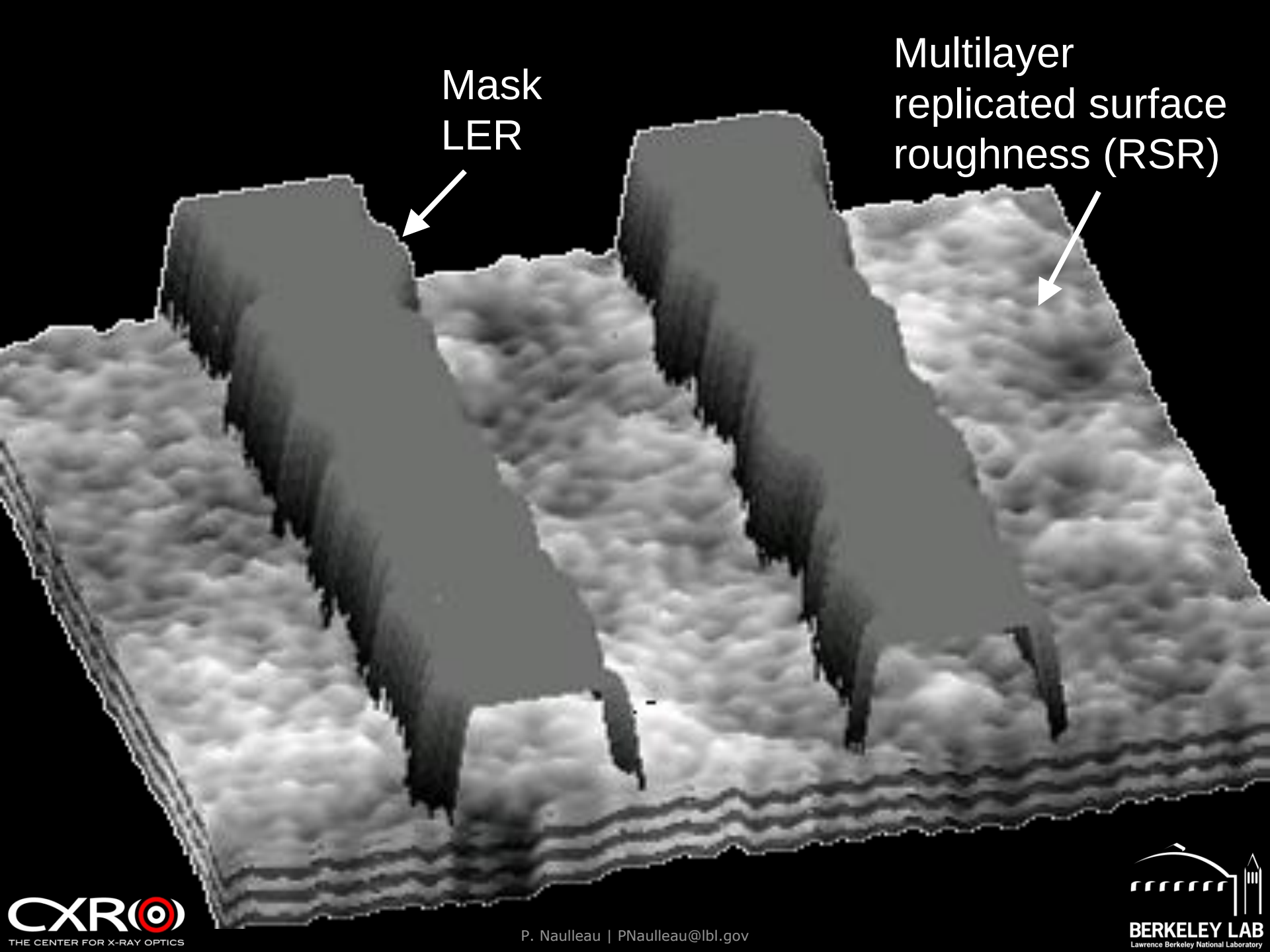
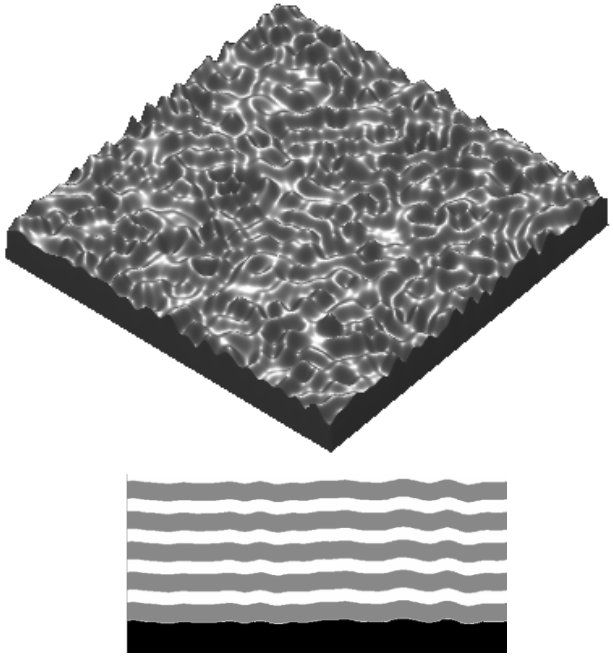
Funding by SEMATECH


Mask
LER
Multilayer
replicated surface
roughness (RSR)

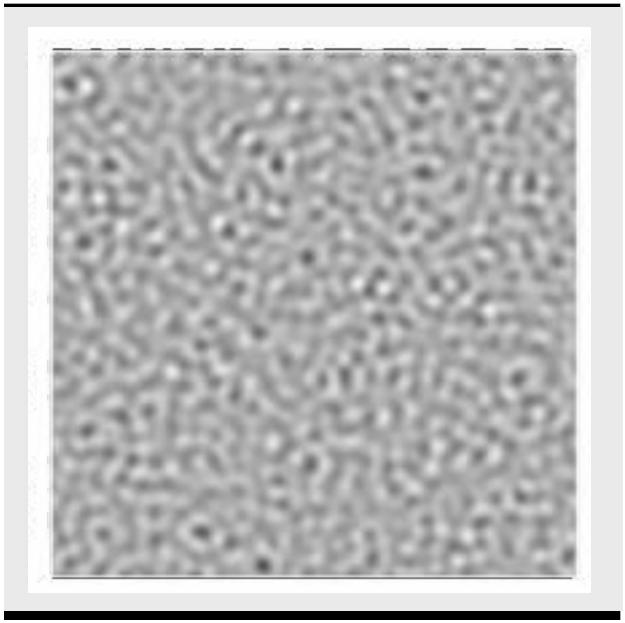
Band-limited imaging and propagation transforms replicated surface (phase) roughness to intensity speckle

230 pm RSR



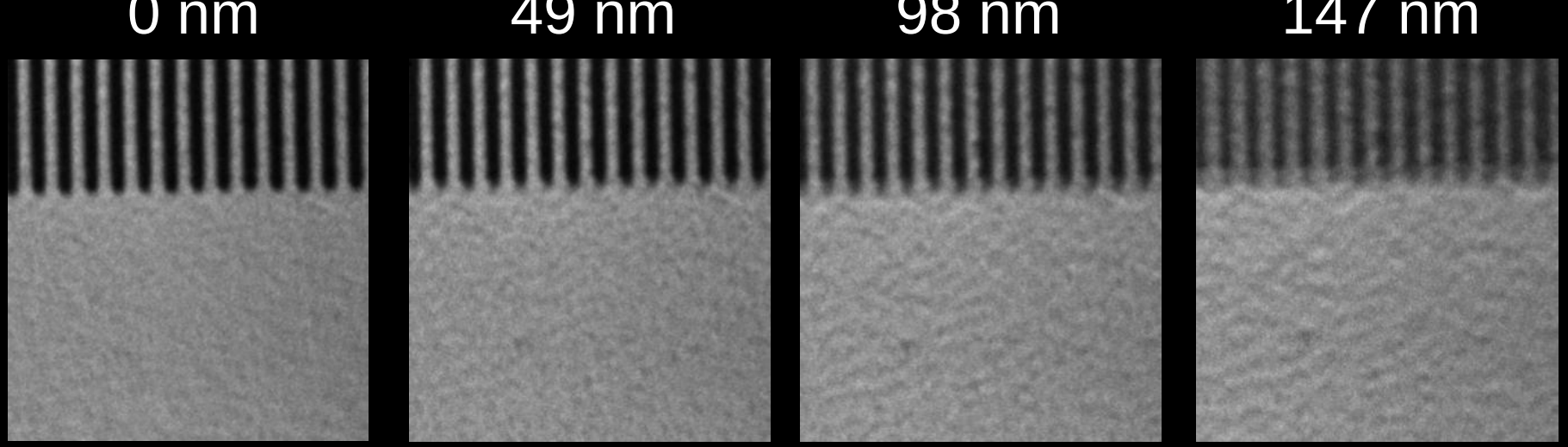
50-nm defocus
$\sigma = 0.3$

Contrast = 9%



Speckle directly observed with EUV microscope

Defocus

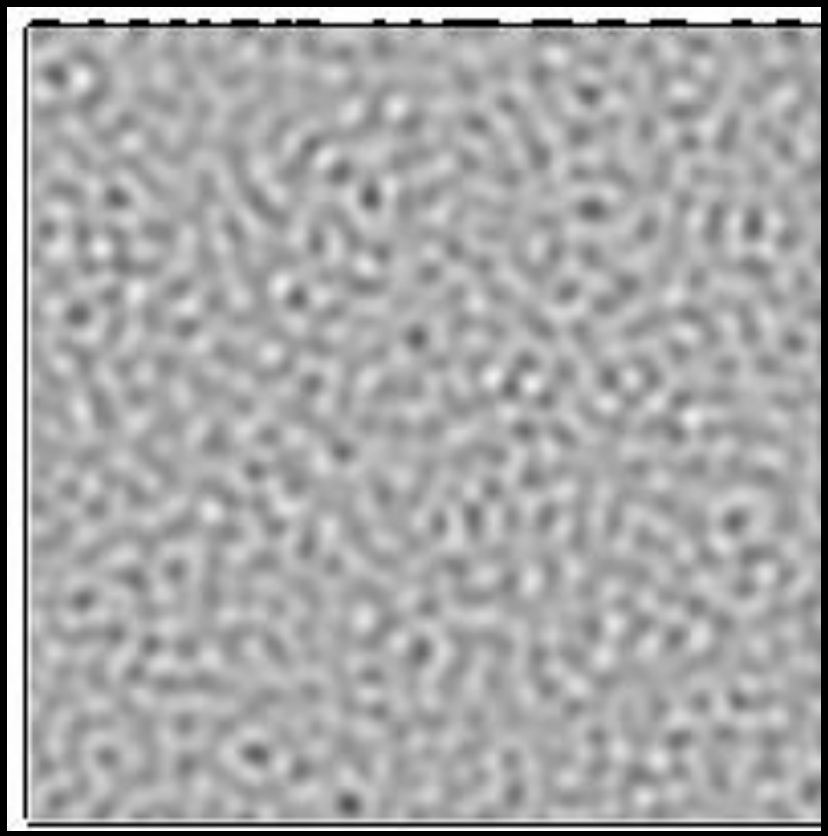


Images from SEMATECH Berkeley AIT courtesy of Ken Goldberg, LBNL

Simplified computation of roughness effect on LER

Compute speckle contrast:

$$\frac{\sigma_I}{\mu_I}$$



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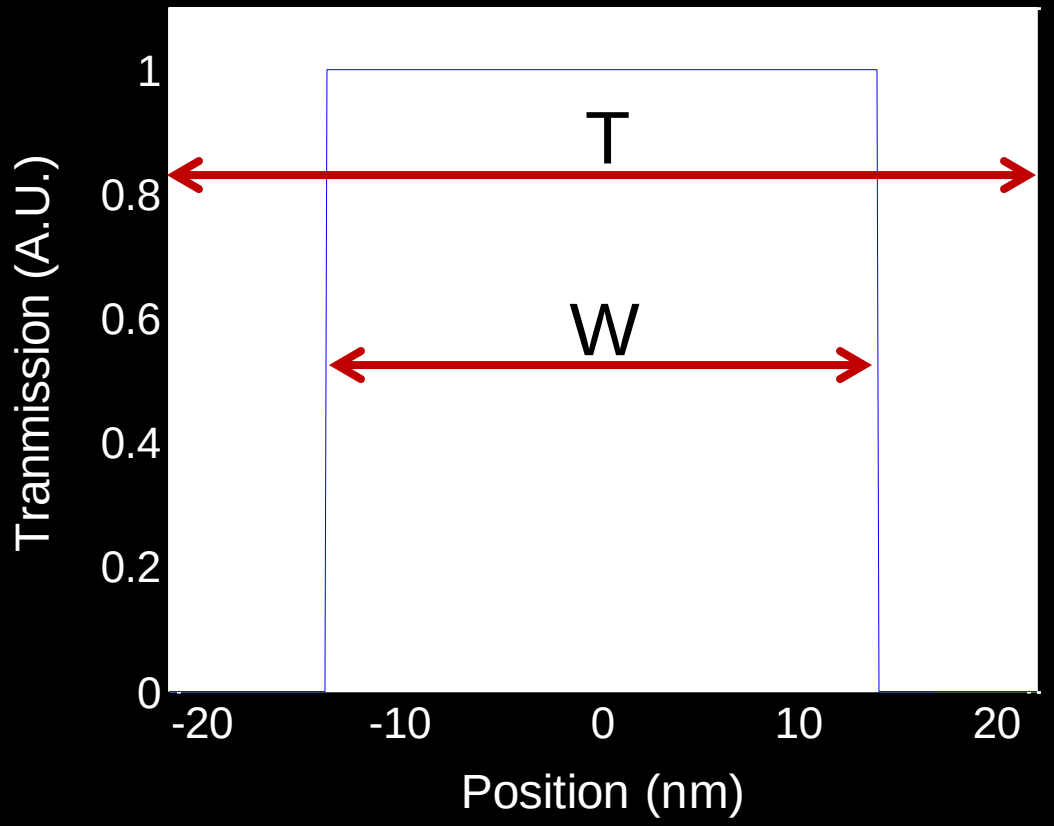
Simplified computation of roughness effect on LER

Determine open ratio for feature:

$$\frac{T}{W}$$



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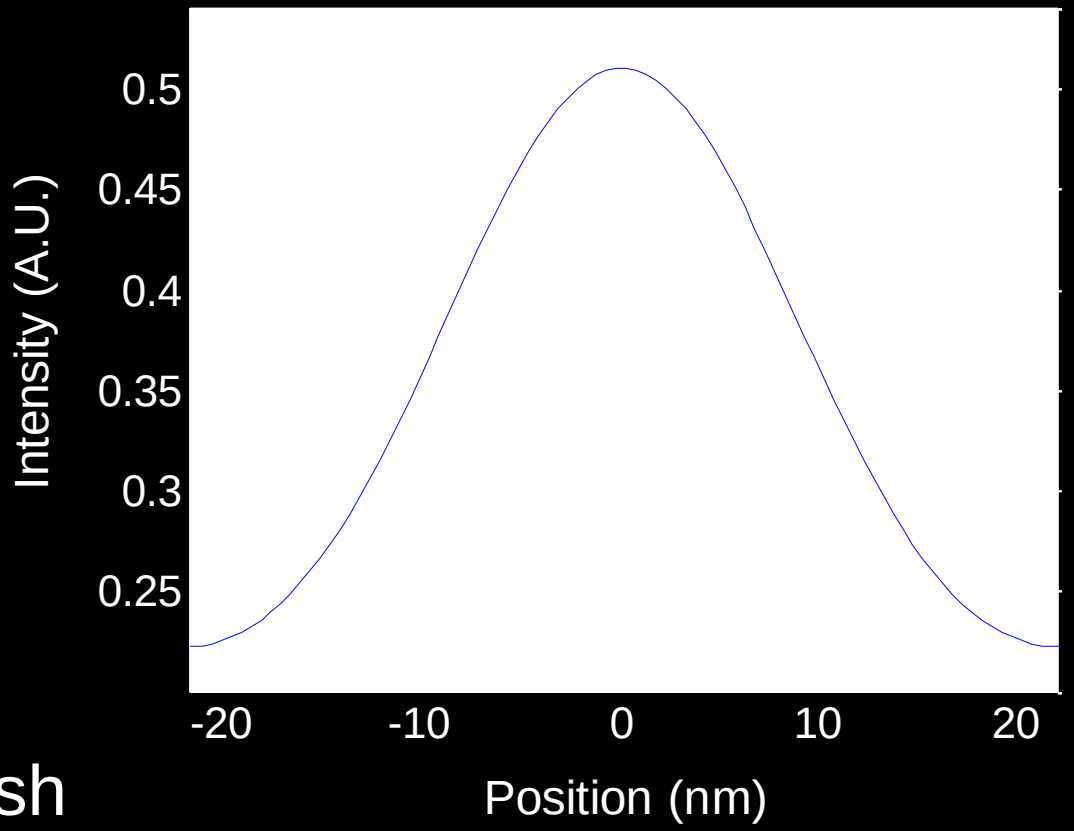
Simplified computation of roughness effect on LER

Compute ILS for feature:

$$\frac{1}{I_{thresh}} \cdot \frac{dI}{dx}\bigg|_{I_{thresh}}$$



Simplified computation of roughness effect on LER

Estimate LER:

$$3 \cdot \frac{1}{\sqrt{T/W}} \cdot \frac{\sigma_I}{\mu_I} \cdot \frac{1}{I_{thresh}} \cdot \left. \frac{dI}{dx} \right|_{I_{thresh}}$$

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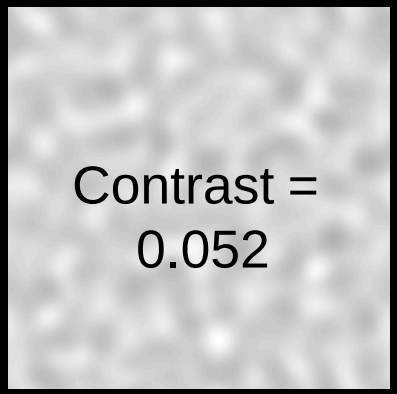
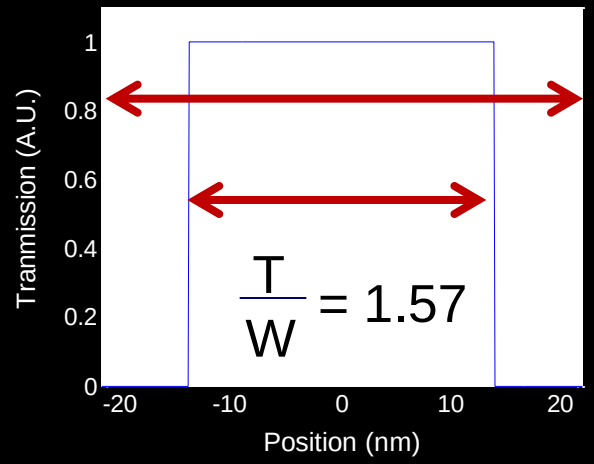
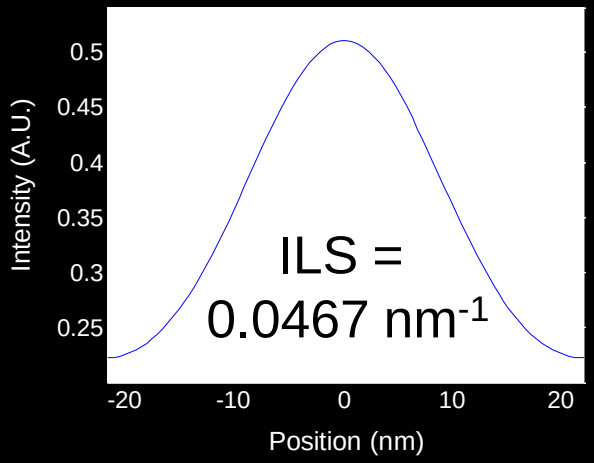
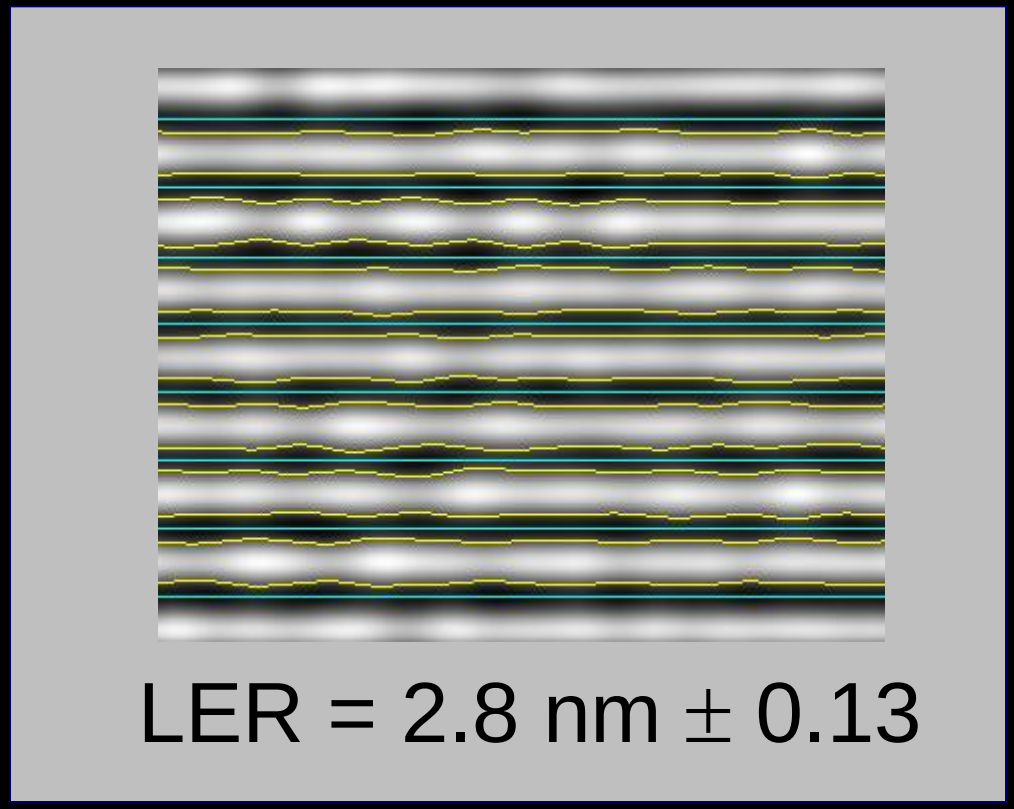


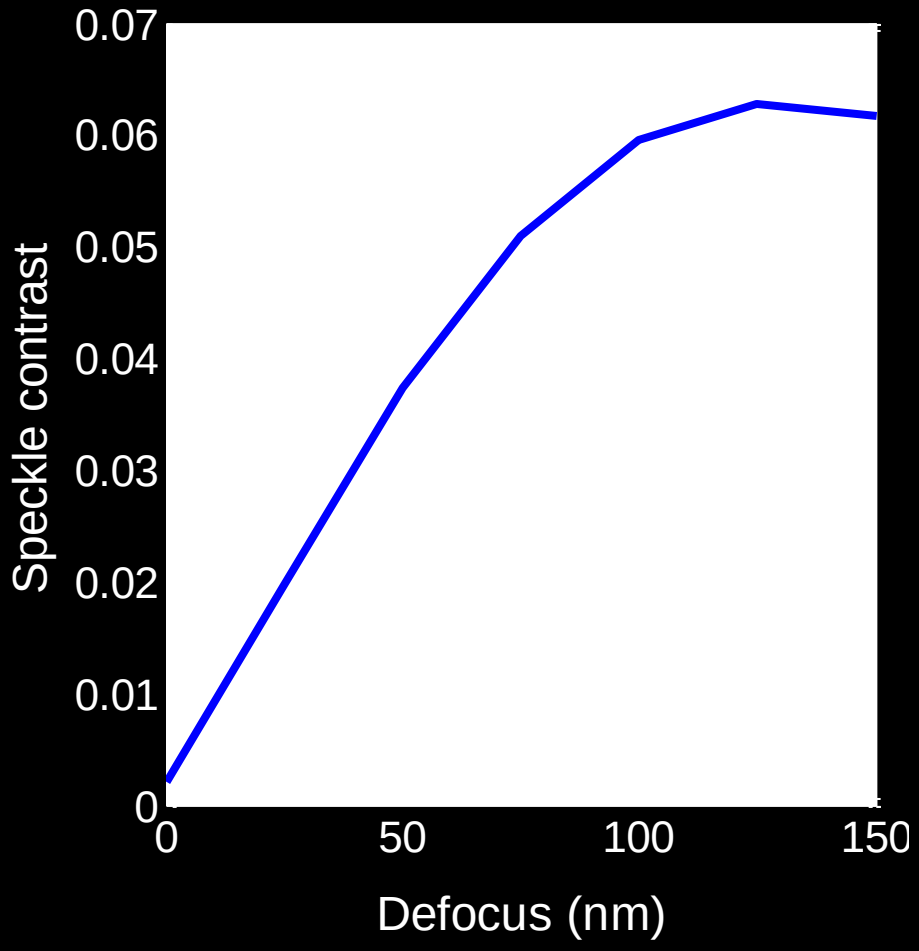


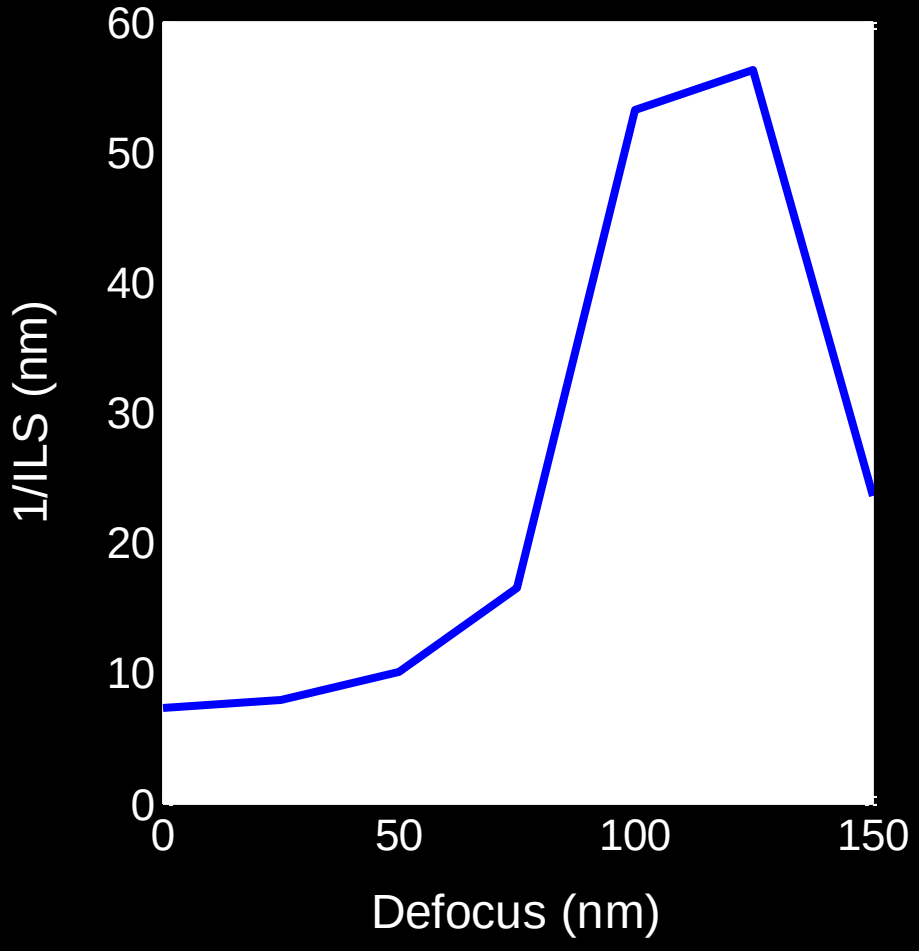




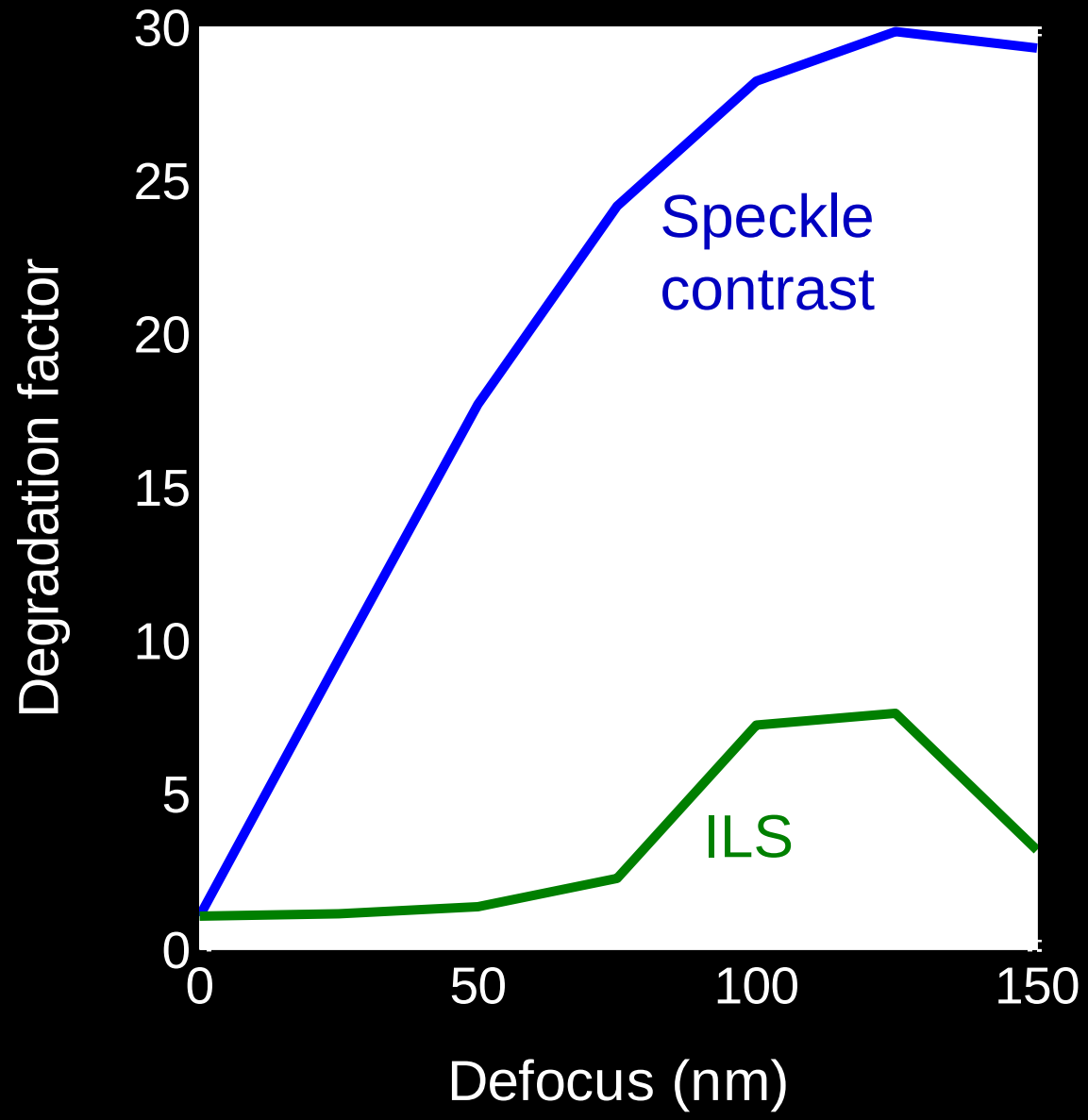
$$3 \cdot \frac{1}{\sqrt{1.57}} \cdot 0.052 \cdot \frac{1}{0.0467} = 2.7 \text{ nm}$$

LER degradation through focus

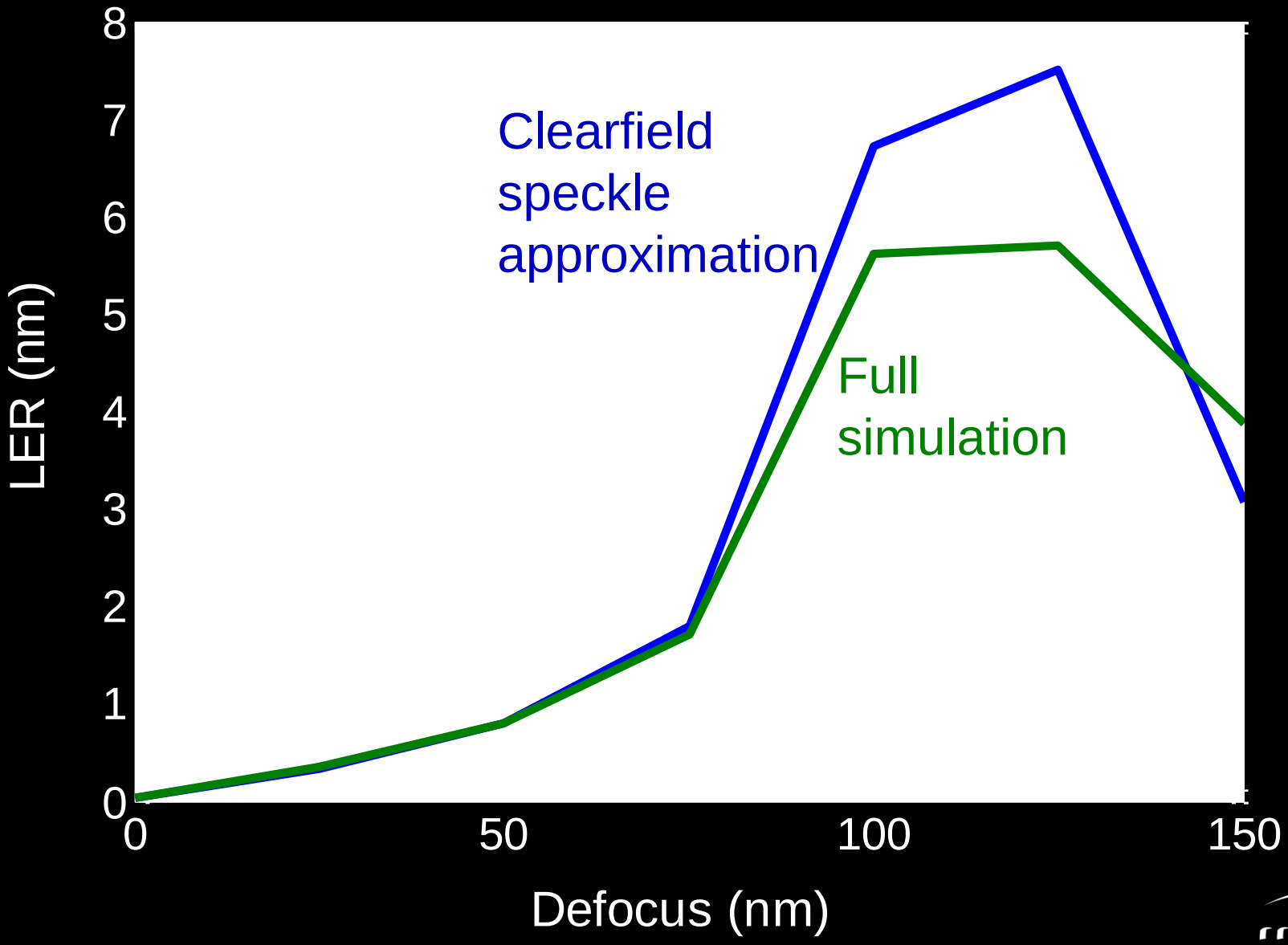




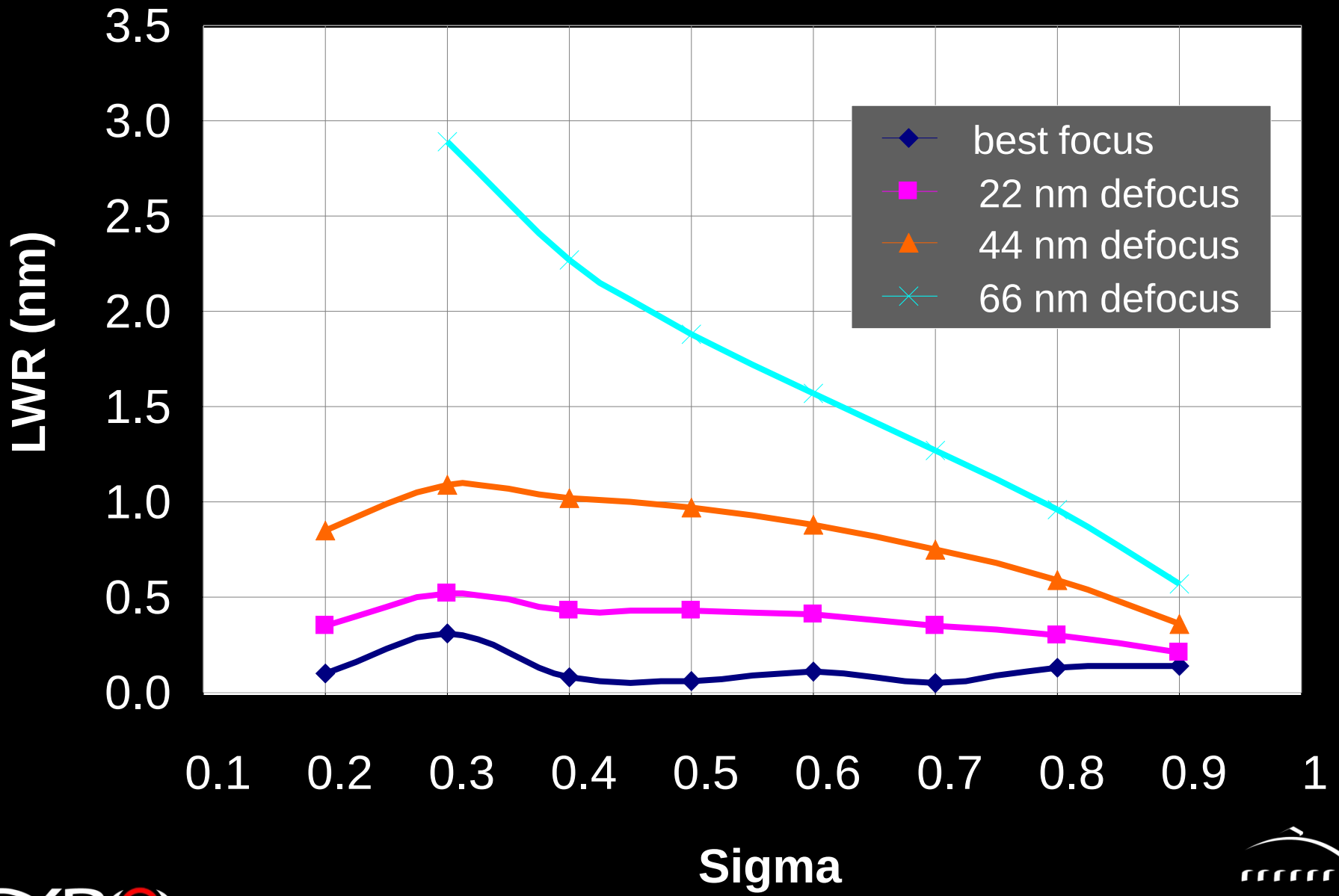
LER degradation through focus



LER degradation through focus



Partial coherence



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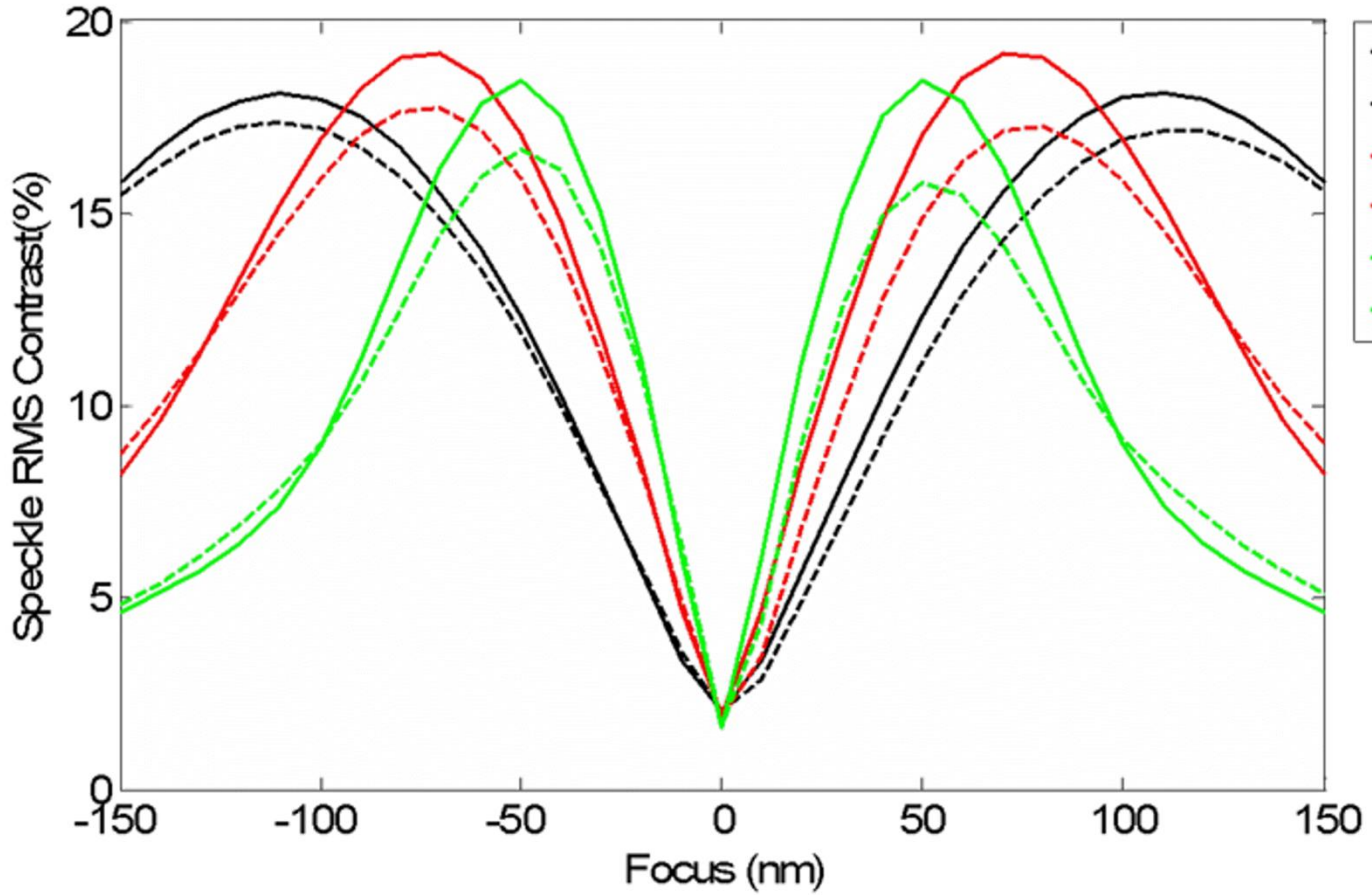
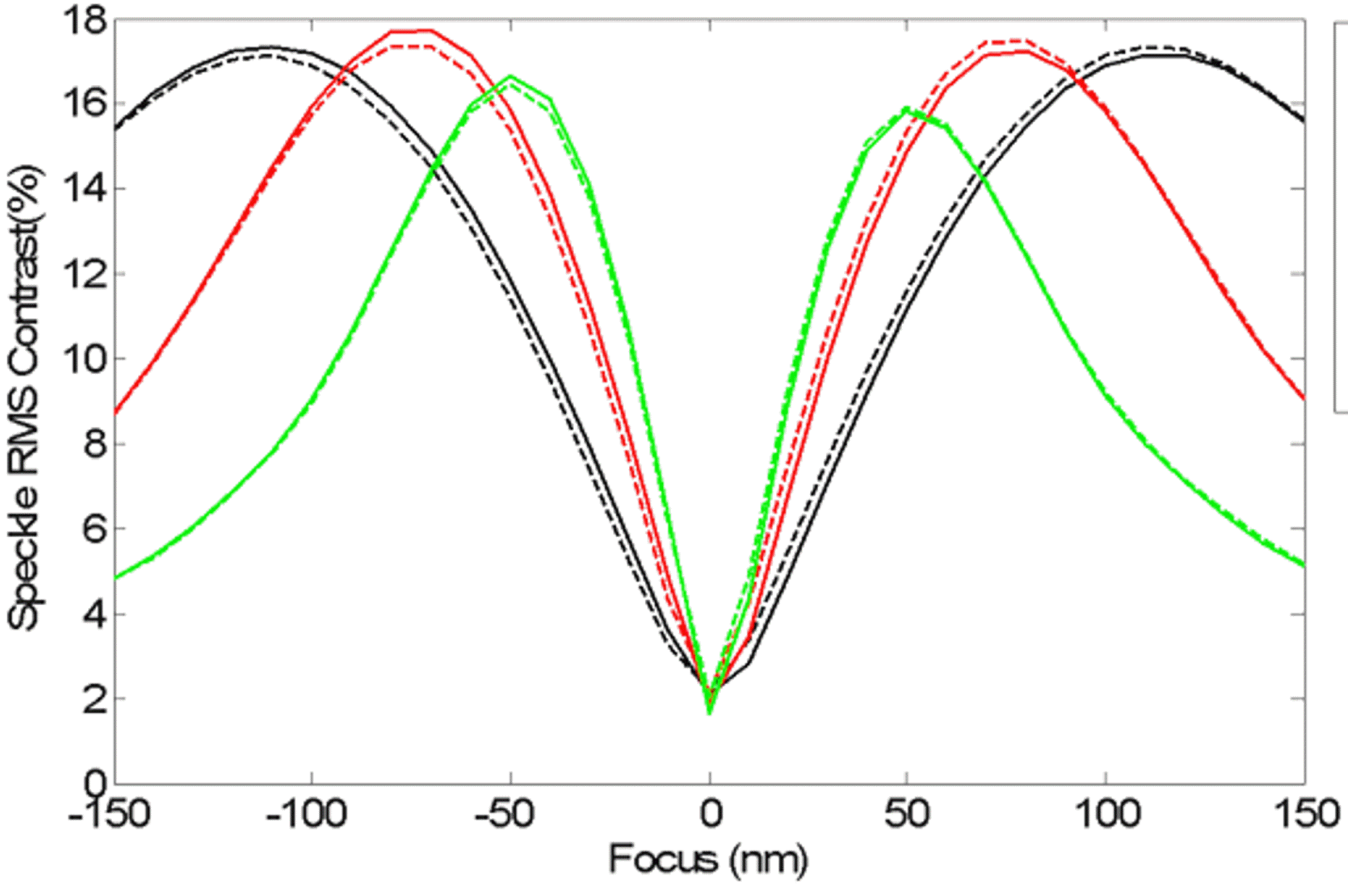
Is 2D simulation good enough?

Good match in region of interest even at high NA



Speckle effect independent of angle of incidence



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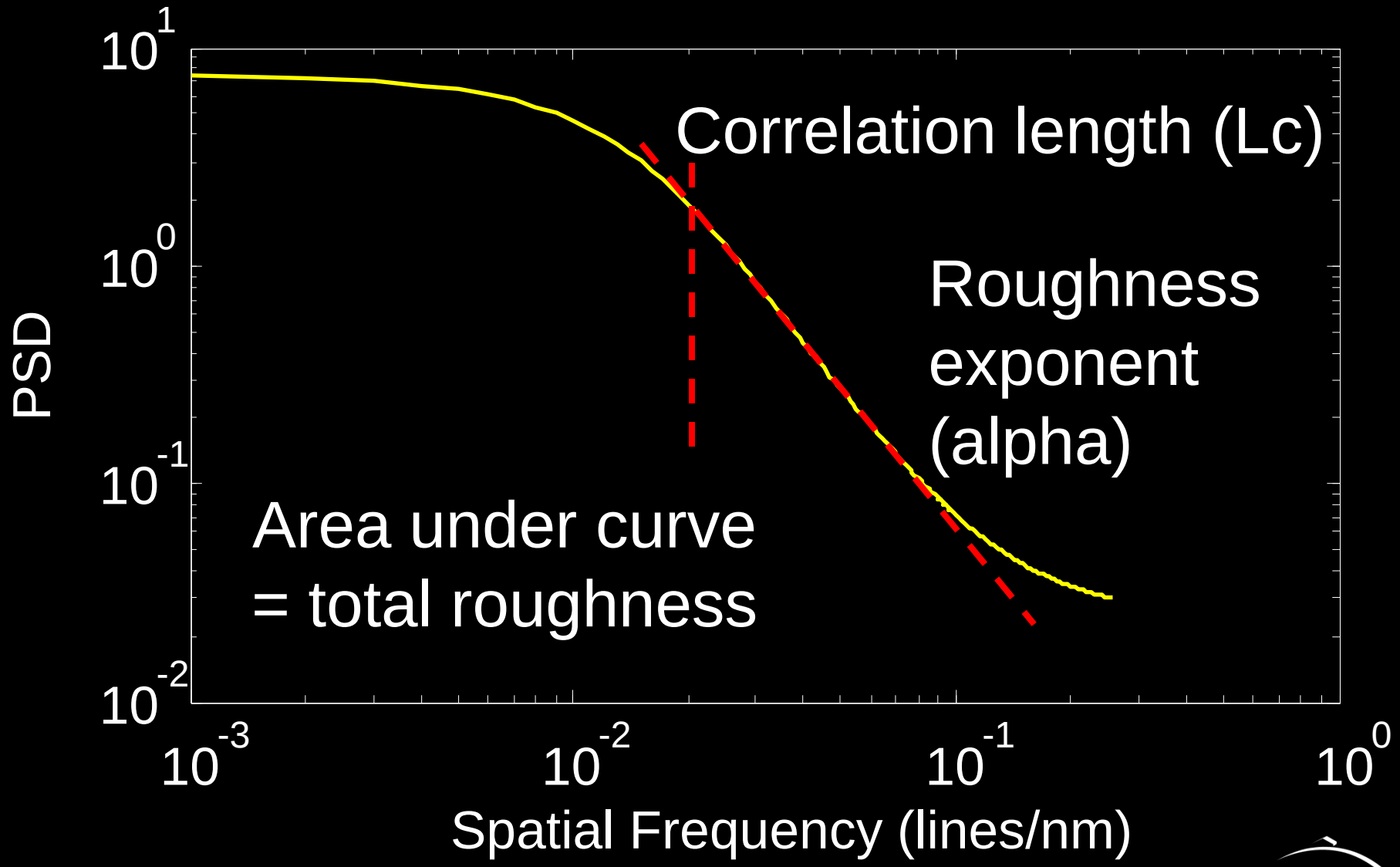
What about the mask characteristics?

Characterizing roughness



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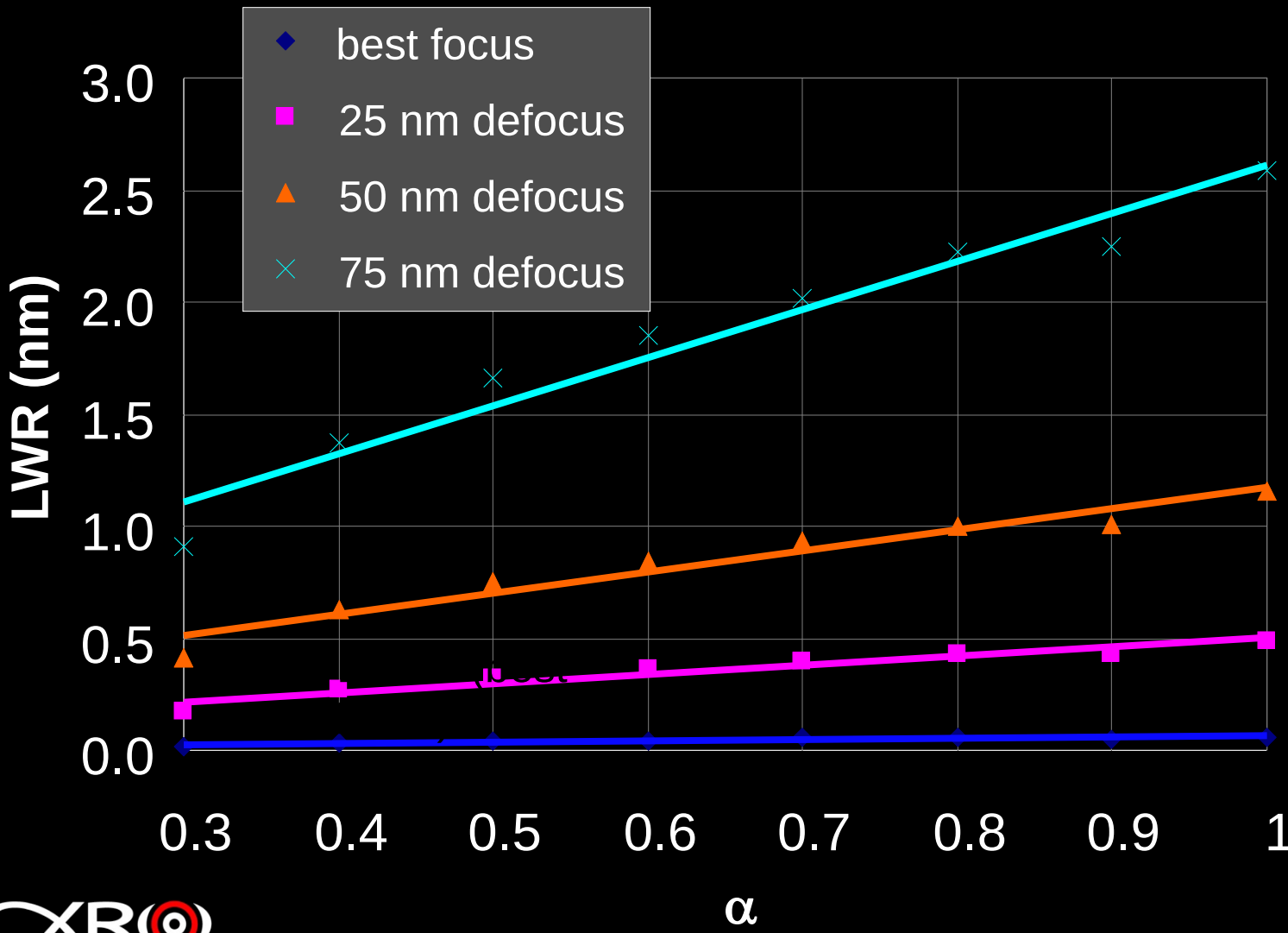
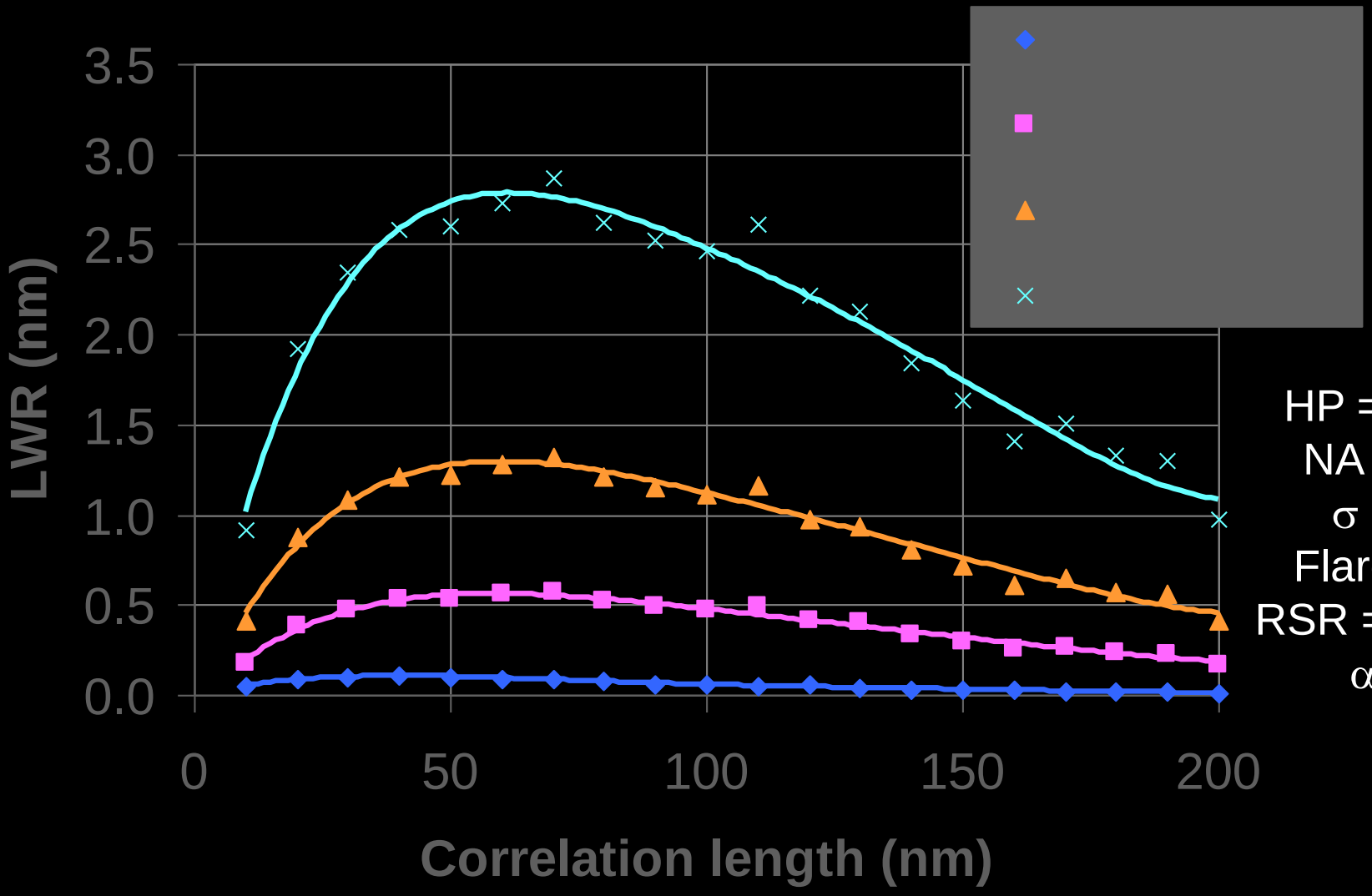
LER increases monotonically with roughness exponent



HP = 22 nm
NA = 0.32
σ = 0.5
Flare = 5%
Lc = 100 nm
RSR = 100 pm

LER strongly dependent on roughness correlation length



HP = 22 nm
NA = 0.32
σ = 0.5
Flare = 5%
RSR = 100 pm
α = 1

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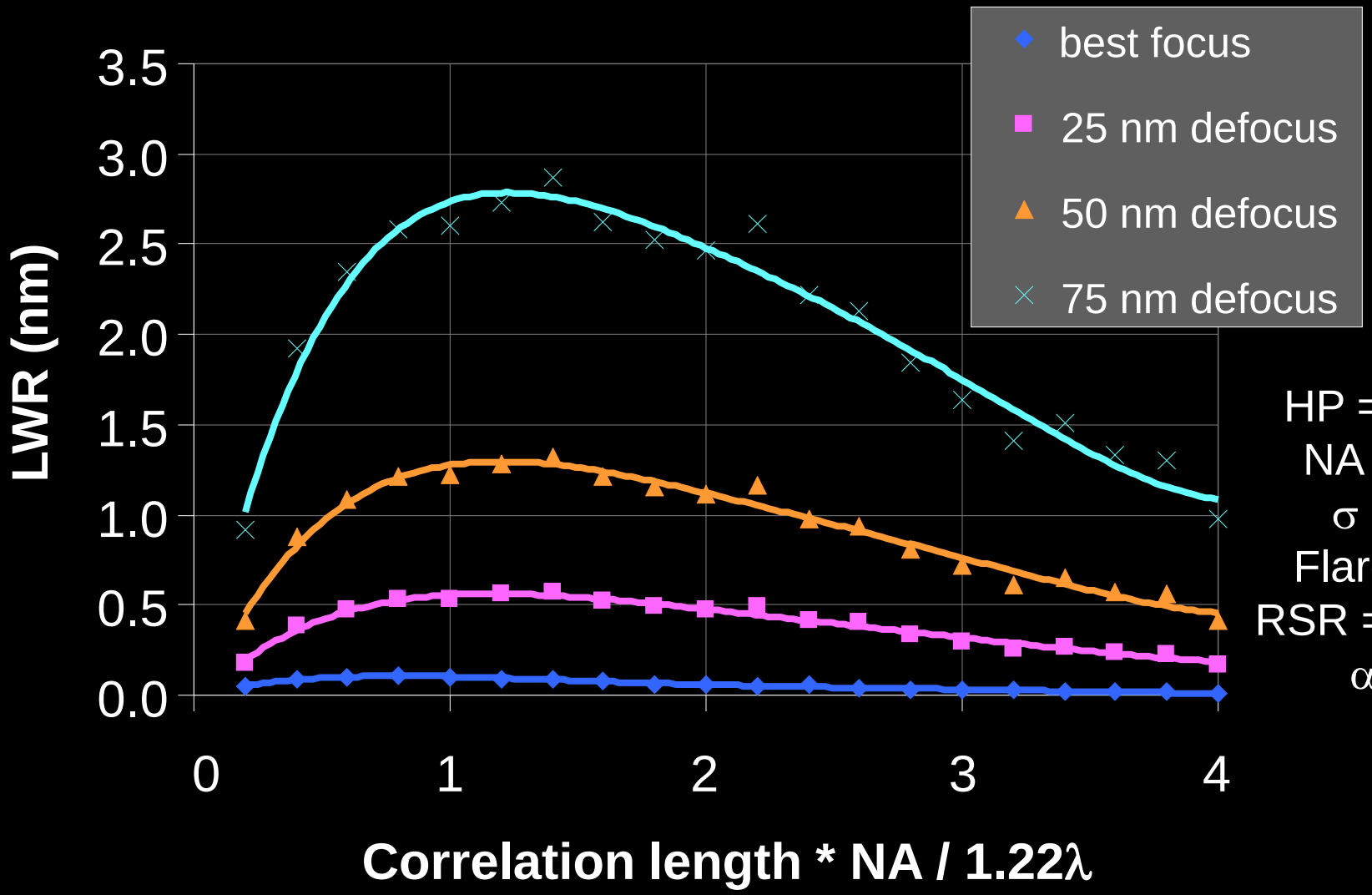
Effect can be minimized by optimizing NA



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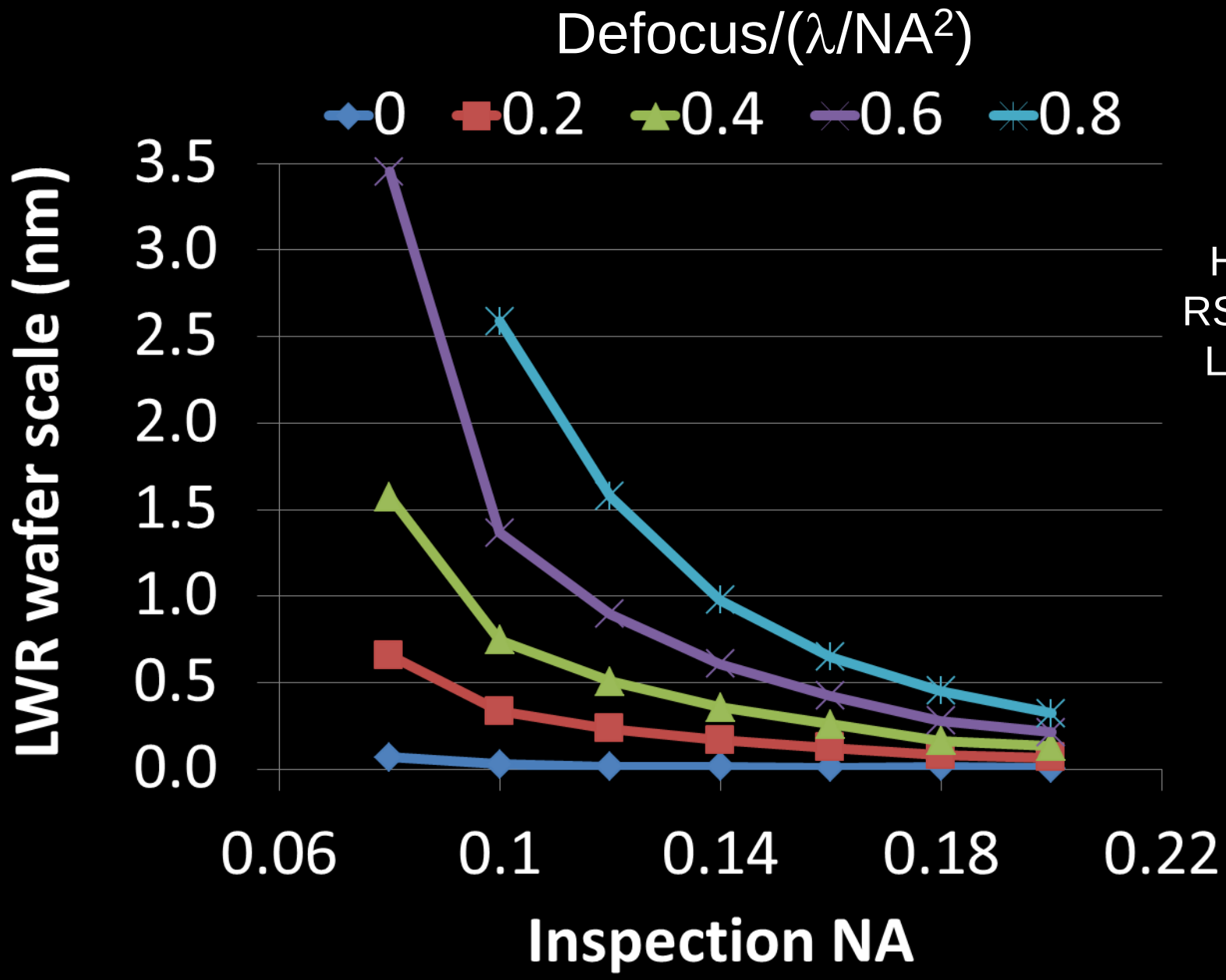
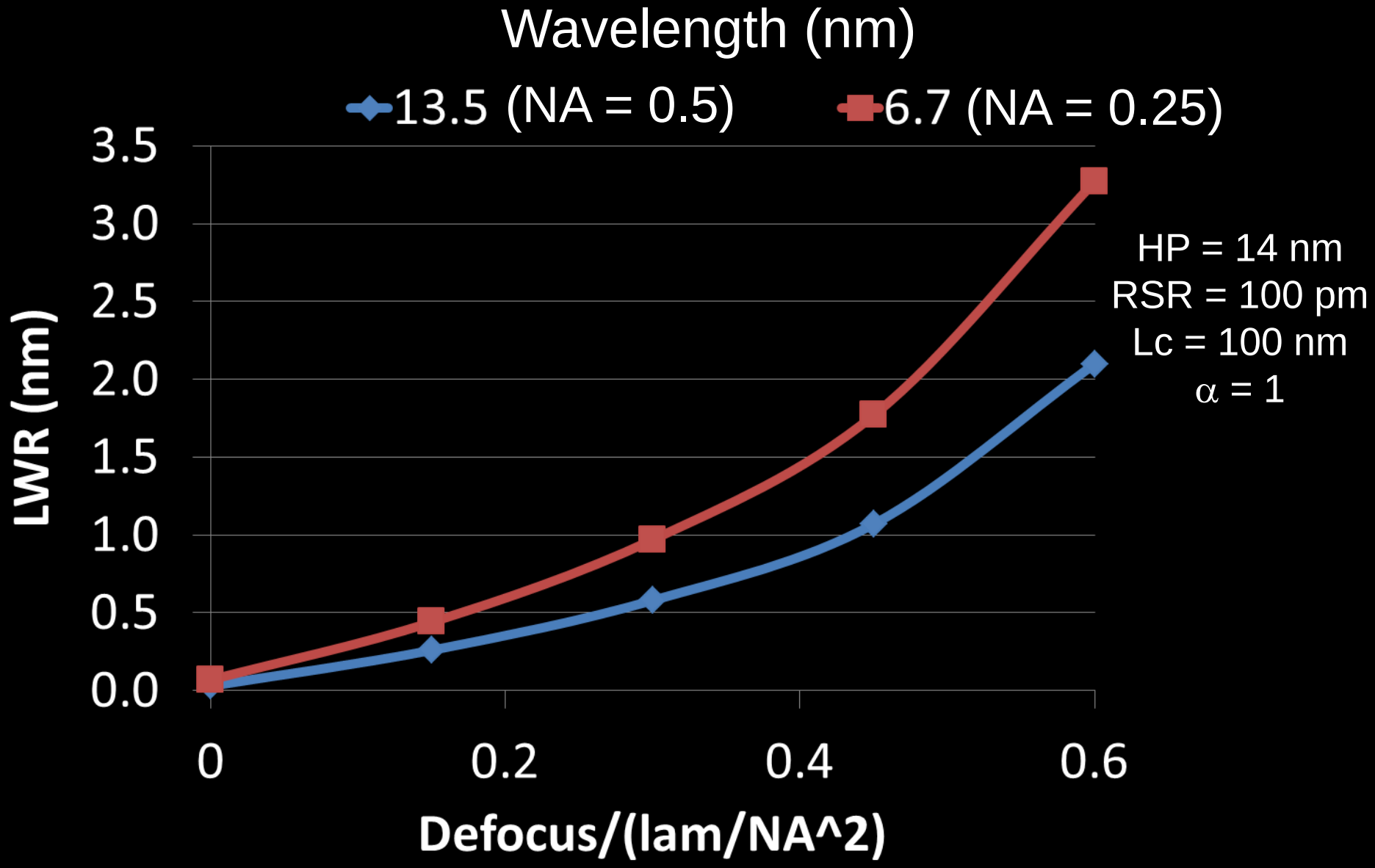


HP = 22 nm
RSR = 100 pm
Lc = 100 nm
α = 1


Wavelength (nm)
13.5 (NA = 0.5)
6.7 (NA = 0.25)
LWR (nm)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
0.2
0.4
0.6
Defocus/(lam/NA^2)
HP = 14 nm
RSR = 100 pm
Lc = 100 nm
α = 1

What about capping layer roughness?

Sensitivity to capping layer roughness highly dependent on material and much lower than RSR

Capping Material	Double Pass Phase Shift per nm of material	Roughness Equivalent to 50 pm RSR*
Si	0.002°	730 nm
Ru	6°	0.44 nm
C	2°	1.25 nm

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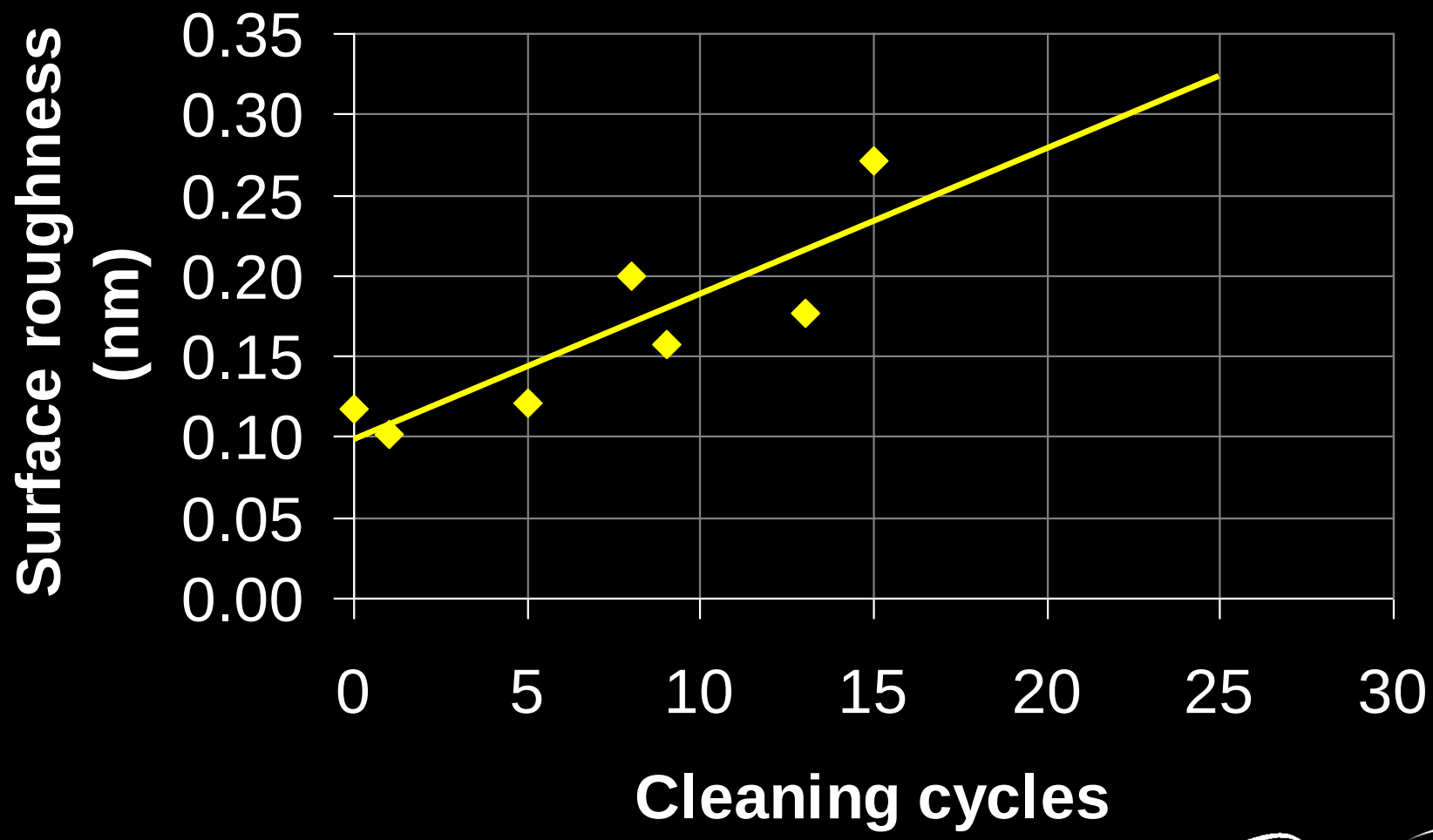
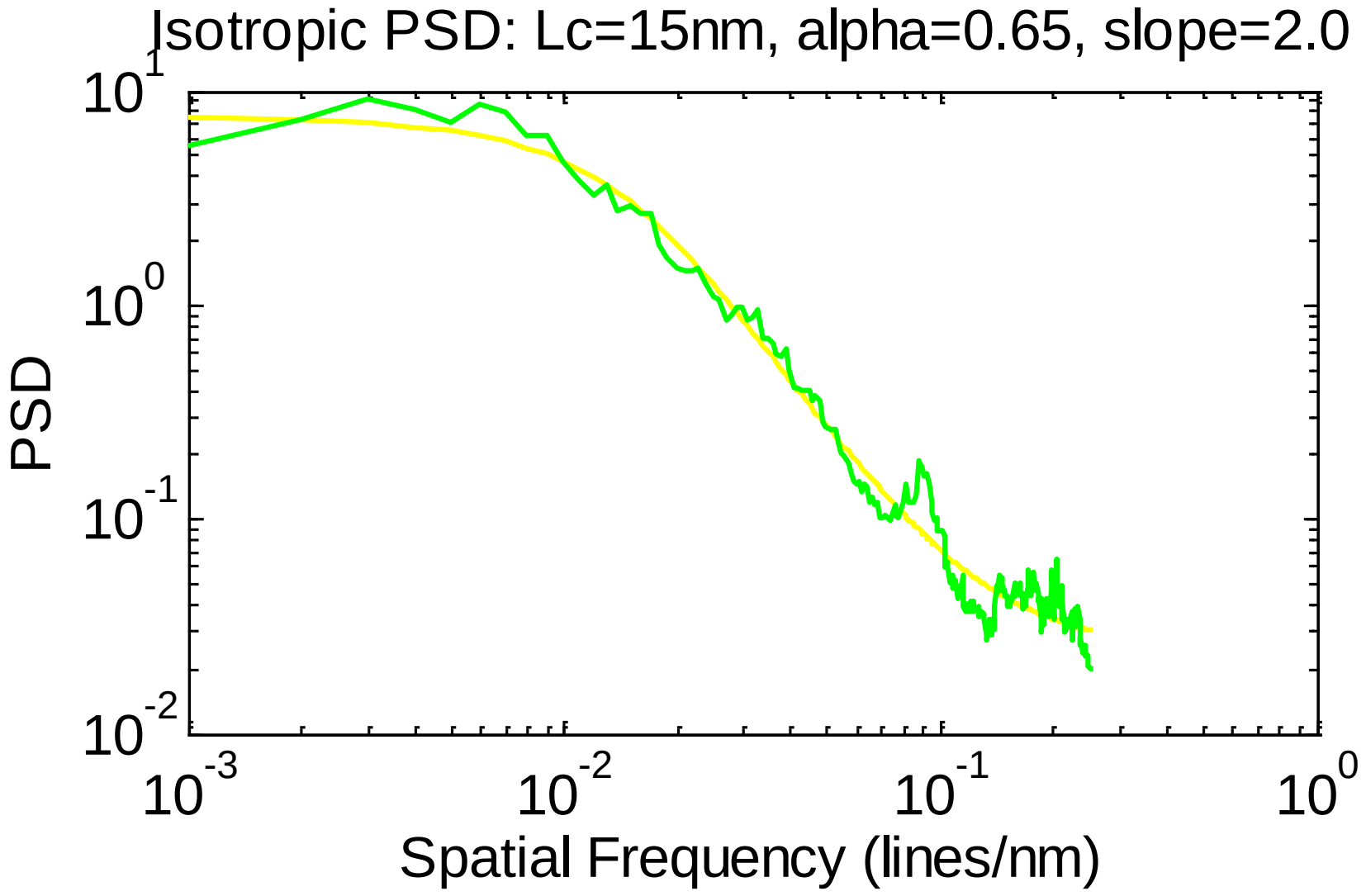
EUV masks must undergo many cleaning cycles to meet lifetime targets

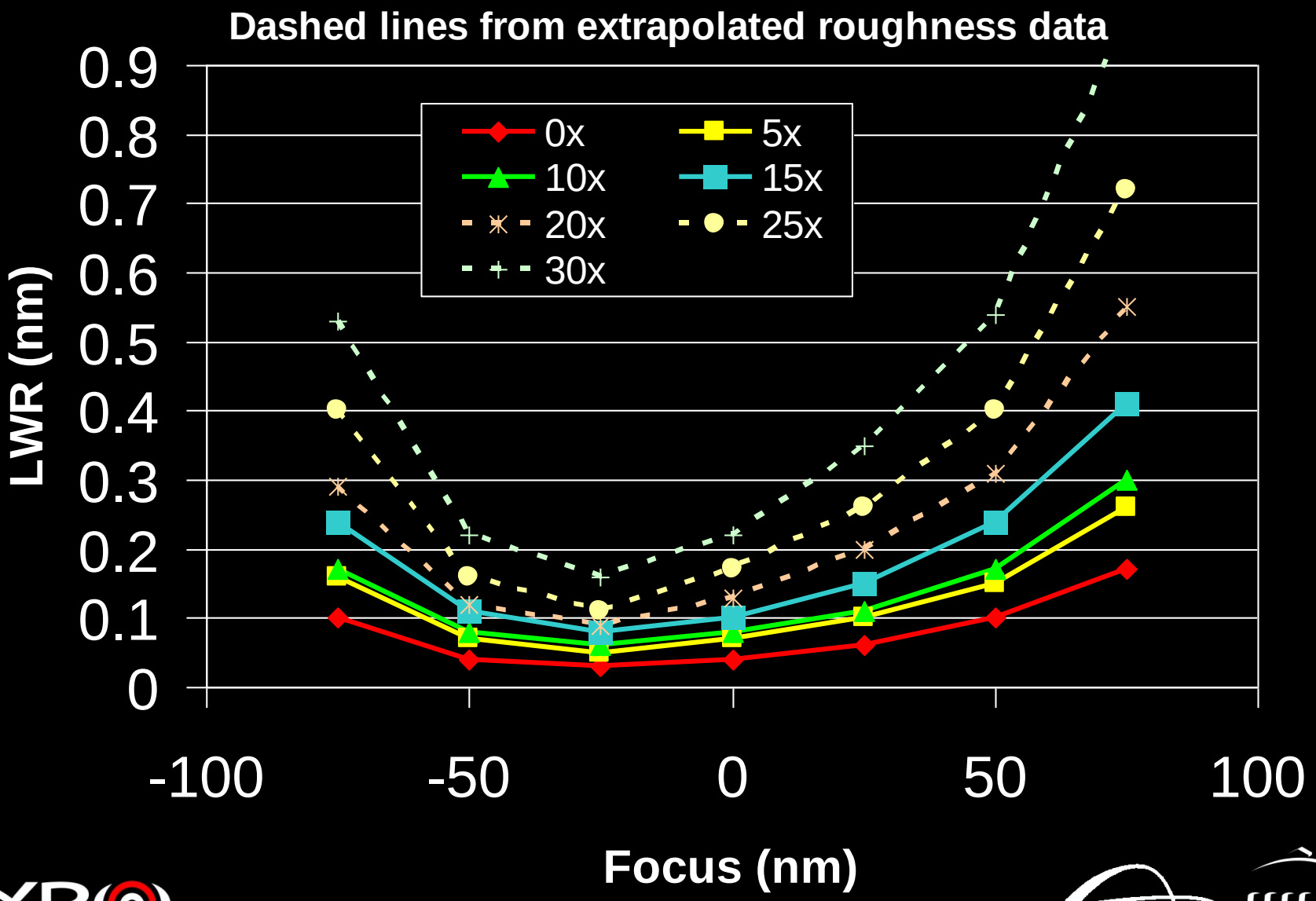
Data courtesy of Abbas Rastegar, SEMATECH



Cleaning-induced capping roughness higher frequency than RSR



Cleaning damage causes increased LWR



Summary

- Mask phase roughness must be carefully considered when using defocus to enhance detection
- Increasing inspection NA is highly effective in reducing mask roughness effects
- The problem is worse for low NA 6.7 nm than high NA 13.5 nm

Acknowledgements

- Frank Goodwin, Abbas Rastegar, SEMATECH
- B. McClinton, Simi George, K. Goldberg, LBNL

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Thank You

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